

Cryptanalysis of the LAKE Hash Family

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Abstract. We analyse the security of the cryptographic hash function LAKE-256 proposed at FSE 2008 by Aumasson, Meier and Phan. By exploiting non-injectivity of some of the building primitives of LAKE, we show three different collision and near-collision attacks on the compression function. The first attack uses differences in the chaining values and the block counter and finds collisions with complexity 2^{33} . The second attack utilizes differences in the chaining values and salt and yields collisions with complexity 2^{42} . The final attack uses differences only in the chaining values to yield near-collisions with complexity 2^{99} . All our attacks are independent of the number of rounds in the compression function. We illustrate the first two attacks by showing examples of collisions and near-collisions.

1 Introduction

The recent cryptanalytical results on the cryptographic hash functions following the attacks on MD5 and SHA-1 by Wang et al. [17, 16, 15] have seriously undermined the confidence in many currently deployed hash functions. Around the same time, new generic attacks such as multicollision attack [7], long message second preimage attack [9] and herding attack [8], exposed some undesirable properties and weaknesses in the popular Merkle-Damgård (MD) construction [12, 5]. These developments have renewed the interest in the design of hash functions. Subsequent announcement by NIST of the SHA-3 hash function competition, aiming at augmenting the FIPS 180-2 [13] standard with a new cryptographic hash function, has further stimulated the interest in the design and analysis of hash functions.

The hash function family LAKE [1], presented at FSE 2008, is one of the new designs. It follows the design principles of the HAIFA framework [2, 3] – a strengthened alternative to the MD construction.

As the additional inputs to the compression function, LAKE uses a random value (also called salt) and an index value, which counts the number of bits/blocks in the input message processed so far.

The first analysis of LAKE, presented by Mendel and Schläffer [11], has shown collisions for 4 out of 8 rounds with complexity of 2^{109} . The main idea used in the attack is the non-injectivity of one of the internal functions. This property allows to introduce difference in the message words which is canceled immediately when the difference goes through the non-injective function.

Our contributions Our attacks focus on finding collisions for the compression function of LAKE. Let $f(H, M, S, t)$ be a compression function of a HAIFA hash function using chaining values H , message block M , salt S and the block index t .

We present the following three types of collision attacks: The first attack uses differences in the chaining values H and block index t , so we are looking for collisions of form $f(H, M, S, t) = f(H', M, S, t')$. We call it (H, t) -type attack. The complexity of this attack is 2^{33} compression calls.

The second attack deals with the differences injected in the chaining values and salt S , we call it (H, S) -attack. We present how to find near-collisions of the compression function with complexity 2^{30} compression calls and extend it to full collisions with complexity 2^{42} .

The final attack, called H -type attack, uses only differences in the chaining values to find near-collisions for the compression function with complexity 2^{99} .

The success of our collision attacks rely on solving the systems of equations that originate from the differential conditions imposed by the attacks. We present some efficient methods to solve the systems of equations.

Our attacks demonstrate that increasing the number of compression functions rounds of LAKE does not increase its security as they all aim at canceling the differences within the first `ProcessMessage` function of the compression function.

2 Description of LAKE

In this section, we provide a brief description of the LAKE compression function, skipping details that are not relevant to our attacks. See [1] for details.

Basic functions – LAKE uses two functions f and g defined as follows:

$$\begin{aligned} f(a, b, c, d) &= (a + (b \vee C_0)) + ((c + (a \wedge C_1)) \ggg 7) + \\ &\quad ((b + (c \oplus d)) \ggg 13) \quad , \\ g(a, b, c, d) &= ((a + b) \ggg 1) \oplus (c + d) \quad , \end{aligned}$$

where each variable is a 32-bit word and C_0, C_1 are constants.

The compression function of LAKE has three integral components: SaltState, ProcessMessage and FeedForward. The functionality of these components are described in Algorithms 1, 2 and 3, respectively. The whole compression function of LAKE is described in Algorithm 4. Our attack does not depend on the constants C_i for $i = 0, \dots, 15$ and hence we do not provide their actual values here.

Input: $H = H_0 \parallel \dots \parallel H_7, S = S_0 \parallel \dots \parallel S_3, t = t_0 \parallel t_1$
Output: $F = F_0 \parallel \dots \parallel F_{15}$
for $i = 0, \dots, 7$ **do**
 | $F_i = H_i;$
end
 $F_8 = g(H_0, S_0 \oplus t_0, C_8, 0);$
 $F_9 = g(H_1, S_1 \oplus t_1, C_9, 0);$
for $i = 10, \dots, 15$ **do**
 | $F_i = g(H_i, S_i, C_i, 0);$
end

Algorithm 1: LAKE's SaltState

Input: $F = F_0 \parallel \dots \parallel F_{15}, M = M_0 \parallel \dots \parallel M_{15}, \sigma$
Output: $W = W_0 \parallel \dots \parallel W_{15}$
for $i = 0, \dots, 15$ **do**
 | $L_i = f(L_{i-1}, F_i, M_{\sigma(i)}, C_i);$
end
 $W_0 = g(L_{15}, L_0, F_0, L_1);$
 $L_0 = W_0;$
for $i = 1, \dots, 15$ **do**
 | $W_i = g(W_{i-1}, L_i, F_i, L_{i+1});$
end

Algorithm 2: LAKE's ProcessMessage

Input: $W = W_0 \parallel \dots \parallel W_{15}, H = H_0 \parallel \dots \parallel H_7, S = S_0 \parallel \dots \parallel S_3, t = t_0 \parallel t_1$
Output: $H = H_0 \parallel \dots \parallel H_7$
 $H_0 = f(W_0, W_8, S_0 \oplus t_0, H_0);$
 $H_1 = f(W_1, W_9, S_1 \oplus t_1, H_1);$
for $i = 2, \dots, 7$ **do**
 | $H_i = f(W_i, W_{i+8}, S_i, H_i);$
end

Algorithm 3: LAKE's FeedForward

Input: $H = H_0 \parallel \dots \parallel H_7, M = M_0 \parallel \dots \parallel M_{15}, S = S_0 \parallel \dots \parallel S_3, t = t_0 \parallel t_1$
Output: $H = H_0 \parallel \dots \parallel H_7$
 $F = \text{SaltState}(H, S, t);$
for $i = 0, \dots, r - 1$ **do**
 $F = \text{ProcessMessage}(F, M, \sigma_i);$
end
 $H = \text{FeedForward}(F, H, S, t);$

Algorithm 4: LAKE's CompressionFunction

3 Properties and Observations

We first present some properties of the f function used in our analysis.

Observation 1 *Function $f(x, y, z, t)$ is non-injective with respect to the first three arguments x, y, z .*

For example, for x there exists different values x and x' such that $f(x, y, z, t) = f(x', y, z, t)$ for some y, z, t . The same property holds for y and z .

This observation was mentioned by Lucks at FSE'08. Mendel and Schl affer independently found and used this property to successfully attack four out of eight rounds of LAKE-256. Non-injectivity of the function f can be used to cancel a difference in one of the first three arguments of f , when the rest of the arguments are properly fixed.

The following observation of the rotation effect on the modular addition allows us to simplify the analysis of the behavior of f .

Lemma 1 ([6]) $(a + b) \ggg k = (a \ggg k) + (b \ggg k) + \alpha - \beta \cdot 2^{n-k}$, where $\alpha = \mathbf{1}[a_k^R + b_k^R \geq 2^k]$ and $\beta = \mathbf{1}[a_k^L + b_k^L + \alpha \geq 2^{n-k}]$.

From the definition, f can be written as

$$\begin{aligned}
 f(a, b, c, d) = & a + b \vee C_0 + (c \ggg 7) + ((a \wedge C_1) \ggg 7) + (b \ggg 13) \\
 & + ((c \oplus d) \ggg 13) + \alpha_1 + \alpha_2 - \beta_1 \cdot 2^{25} - \beta_2 \cdot 2^{19}, \quad (1)
 \end{aligned}$$

where

$$\begin{aligned}
 \alpha_1 = \mathbf{1}[c_7^L + (a \wedge C_1)_7^L \geq 2^7], & \quad \beta_1 = \mathbf{1}[c_7^R + (a \wedge C_1)_7^R + \alpha_1 \geq 2^{25}], \\
 \alpha_2 = \mathbf{1}[b_{13}^L + (c \oplus d)_{13}^L \geq 2^{13}], & \quad \beta_2 = \mathbf{1}[b_{13}^R + (c \oplus d)_{13}^R + \alpha_2 \geq 2^{19}].
 \end{aligned}$$

Note that α_2 and β_2 are independent of a . Consider now the difference of the outputs of f induced by the difference in the variable a , i.e.

$$\begin{aligned}
 \Delta f &= f(a', b, c, d) - f(a, b, c, d) \\
 &= [a' + (a' \wedge C_1) + \alpha'_1 - \beta'_1 \cdot 2^{25}] - [a + (a \wedge C_1) + \alpha_1 - \beta_1 \cdot 2^{25}] \\
 &= a' + ((a' \wedge C_1) \ggg 7) - [a + ((a \wedge C_1) \ggg 7)] + (\alpha'_1 - \alpha_1) - (\beta'_1 - \beta_1) \cdot 2^{25} \\
 &= f_a(a') - f_a(a) + (\alpha'_1 - \alpha_1) - (\beta'_1 - \beta_1) \cdot 2^{25},
 \end{aligned}$$

where $f_a(a) \stackrel{\text{def}}{=} a + ((a \wedge C_1) \ggg 7)$.

A detailed analysis (cf. Lemma 5) shows that given random a, a' and c , $P(\alpha_1 = \alpha'_1, \beta_1 = \beta'_1) = \frac{4}{9}$, so with probability $\frac{4}{9}$, a collision for f_a is also a collision of f when input difference is in a only. Let us call this a *carry effect*. However, if we have control over the variable c , we can adjust the values of $\alpha_1, \alpha'_1, \beta_1, \beta'_1$ and always satisfy this condition. From here we can see that $(a + b) \ggg k$ is not a good mixing function when we are considering modular differences.

This reasoning can be repeated for differences in the variable b and similarly for differences in a pair of the variables c, d . It is easy to see that also for those cases, with a high probability, collisions in f happen when the following functions collide

$$\begin{aligned} f_b(b) &\stackrel{\text{def}}{=} b \vee C_0 + (b \ggg 13) , \\ f_{cd}(c, d) &\stackrel{\text{def}}{=} (c \ggg 7) + ((c \oplus d) \ggg 13) . \end{aligned}$$

So, when we follow differences in only one or two variables, we can consider only those variables without the side effects from other variables. We summarize above observations as follows:

Observation 2 *Collisions or output differences of f for input differences in one variable can be made independent from the values of other variables.*

We denote the set of solutions for f_a and f_b with respect to input pairs and modular differences as

$$\begin{aligned} S_{f_a} &\stackrel{\text{def}}{=} \{(x, x') | f_a(x) = f_a(x')\} , & S_{f_a}^A &\stackrel{\text{def}}{=} \{x - x' | f_a(x) = f_a(x')\} , \\ S_{f_b} &\stackrel{\text{def}}{=} \{(x, x') | f_b(x) = f_b(x')\} , & S_{f_b}^A &\stackrel{\text{def}}{=} \{x - x' | f_b(x) = f_b(x')\} . \end{aligned}$$

Choose the odd elements from $S_{f_b}^A$ and define them to be $S_{f_{b_{odd}}}^A$. Note that we can easily precompute all the above solution sets using 2^{32} evaluations of the appropriate functions and 2^{32} words of memory (or some more computations with proportionally less memory).

4 (H, t)-type Attack

First, let us try to attack only the middle procedure of the compression function, i.e. `ProcessMessage` function. It consists of 8 rounds (10 rounds for LAKE-512). In every round, first all of the 16 internal variables are updated by the function f , and then all of them are updated by the function g .

Our differential trail is as follows:

1. Introduce a specially chosen difference in F_0 .
2. After the first application of the function f from all L_i , only L_0 has a non-zero difference.

3. After the first application of the function g none of W_i have any difference.

Let us show that this differential is possible. First let us prove that step 2 is achievable. Considering that $L_i = f(L_{i-1}, F_i, M_{\sigma(i)}, C_i)$ we get that in L_i a difference can be introduced only through L_{i-1} and F_i (message words do not have differences, C_i are simply constants). Note that in the first round $\sigma(i)$ is defined as the identity permutation hence we can write M_i instead of $M_{\sigma(i)}$.

For ΔL_0 we require non-zero difference:

$$\Delta L_0 = f(F_{15}, F'_0, M_0, C_0) - f(F_{15}, F_0, M_0, C_0) \neq 0 \quad (2)$$

For ΔL_1 we require zero difference:

$$\Delta L_1 = f(L'_0, F_1, M_1, C_1) - f(L_0, F_1, M_1, C_1) = 0 \quad (3)$$

From Observation 1, it follows that it is possible to get zero for ΔL_1 .

For all the other $\Delta L_i, i = 2..15$ we require zero difference. This is trivially fulfilled because there are no inputs with difference.

Now, let us take a look at step 3. Again, considering that $W_i = g(W_{i-1}, L_i, F_i, L_{i+1})$, we get that in W_i a difference can be introduced by any of W_{i-1}, L_i, F_i and L_{i+1} .

For ΔW_0 we require zero difference, so we get:

$$\Delta W_0 = g(L_{15}, L'_0, F'_0, L_1) - g(L_{15}, L_0, F_0, L_1) = 0 \quad (4)$$

Note that there are differences in two variables, L_0 and F_0 , hence the equation can be solved.

For the indexes $i = 1..14$ we get:

$$\Delta W_i = g(W_{i-1}, L_i, F_i, L_{i+1}) - g(W_{i-1}, L_i, F_i, L_{i+1}) = 0 \quad (5)$$

All the above equations hold as there are no differences in any of the arguments.

For W_{15} we get:

$$\Delta W_{15} = g(W_{14}, L_{15}, F_{15}, W_0) - g(W_{14}, L_{15}, F_{15}, W_0) = 0$$

Notice that the last argument is not L_0 but rather W_0 because there are no temporal variables that store the previous values of L_i (see `ProcessMessage`). This non-symmetry in the `ProcessMessage` which updates L registers stops the flow of the difference from L_0 to W_{15} .

So, after only one round we can obtain an internal state with all-zero differences in the variables. Then the following rounds can not introduce any difference because there are no differences in the internal state variables or in the message words. So, if we are able to solve the equations that we have got then *the attack is applicable to any number of rounds, i.e. increasing the number of rounds in the `ProcessMessage` function does not improve the security of LAKE.*

Let us take a closer look at our equations. Equation (2) can be written as:

$$\begin{aligned} \Delta L_0 &= f(F_{15}, F'_0, M_0, C_0) - f(F_{15}, F_0, M_0, C_0) = \\ &= (F'_0 \vee C_0) - (F_0 \vee C_0) + [F'_0 + (M_0 \oplus C_0)] \ggg 13 - [F_0 + (M_0 \oplus C_0)] \ggg 13 \end{aligned}$$

Hereafter we will use that $(A+B) \ggg r = (A \ggg r) + (B \ggg r)$ with probability $\frac{1}{4}$ (see [6]). The same holds when rotation to the left is used. Therefore, the above equation can be rewritten as:

$$\Delta L_0 = (F'_0 \vee C_0) - (F_0 \vee C_0) + F'_0 \ggg 13 - F_0 \ggg 13 \quad (6)$$

Equation (3) can be written as:

$$\begin{aligned} \Delta L_1 &= f(L'_0, F_1, M_1, C_1) - f(L_0, F_1, M_1, C_1) = \\ &= L'_0 - L_0 + [M_1 + (L'_0 \wedge C_1)] \ggg 7 - [M_1 + (L_0 \wedge C_1)] \ggg 7 = \\ &= L'_0 - L_0 + (L'_0 \wedge C_1) \ggg 7 - (L_0 \wedge C_1) \ggg 7 = 0 \end{aligned}$$

Equation (4) can be written as:

$$\begin{aligned} \Delta W_0 &= g(L_{15}, L'_0, F'_0, L_1) - g(L_{15}, L_0, F_0, L_1) = \\ &= [(L_{15} + L'_0) \ggg 1] \oplus (F'_0 + L_1) - [(L_{15} + L_0) \ggg 1] \oplus (F_0 + L_1) = 0 \end{aligned}$$

Let us try to extend the collision attack on the `ProcessMessage` function to the full compression function. First, let us deal with the initialization (function `SaltState`).

From the initialization of LAKE, it can be seen that the variables H_0 through H_7 are copied into F_0 through F_7 . The variable F_8 depends on H_0 and t_0 . Similarly, F_9 depends on H_1 and t_1 . The rest of the variables do not depend on either t_0 or t_1 . Since we need a difference in F_0 (for the previous attack on `ProcessMessage` function), we will introduce difference in H_0 . Further, we can follow our previous attack on the `ProcessMessage` block and get collisions after the `ProcessMessage` function. The only difficulty is how to deal with F_8 since it does depend on H_0 which now has a non-zero difference. We use the help of the block index t_0 . By introducing a difference in t_0 we can cancel the difference from H_0 in F_8 . So we get the following equation:

$$\begin{aligned} \Delta F_8 &= g(H'_0, S_0 \oplus t'_0, C_0, 0) - g(H_0, S_0 \oplus t_0, C_0, 0) = \\ &= ((H'_0 + (S_0 \oplus t'_0)) \ggg 1 \oplus C_0) - ((H_0 + (S_0 \oplus t_0)) \ggg 1 \oplus C_0) = 0 \end{aligned}$$

Let $\tilde{t}'_0 = t'_0 \oplus S_0$ and $\tilde{t}_0 = t_0 \oplus S_0$. Then, the above equation gets the following form:

$$\Delta F_8 = H'_0 - H_0 + \tilde{t}'_0 - \tilde{t}_0 = 0$$

Now, let us deal with the last building block of the compression function, the finalization(`FeedForward`). Note that we have differences only in H_0 and t_0 . If we take a glance at the `FeedForward` procedure, we can see that H_0 and t_0 can be found in the same equation, and only there, which defines the new value for H_0 . Since we require zero difference in all of the output variables, we get the following equation:

$$\begin{aligned} \Delta H_0 &= f(F_0, F_8, H'_0, S_0 \oplus t'_0) - f(F_0, F_8, H_0, S_0 \oplus t_0) = \\ &= \tilde{t}'_0 \ggg 7 - \tilde{t}_0 \ggg 7 + (\tilde{t}'_0 \oplus H'_0) \ggg 13 - (\tilde{t}_0 \oplus H_0) \ggg 13 = 0 \end{aligned}$$

This concludes our attack. We have shown that if we introduce a difference only in the chaining value H_0 and the block index t_0 , it is possible to reduce the problem of finding collisions for the compression function of LAKE to the problem of solving a system of equations.

4.1 Solution of the System of Equations

To find a collision for the full compression function of LAKE, we have to solve the equations that were mentioned in the previous sections. As a result, we get the following system (note that $H_0 = F_0$):

$$L'_0 - L_0 + (L'_0 \wedge C_1) \ggg 7 - (L_0 \wedge C_1) \ggg 7 = 0 \quad (7)$$

$$L'_0 - L_0 = (H'_0 \vee C_0) - (H_0 \vee C_0) + H'_0 \ggg 13 - H_0 \ggg 13 \quad (8)$$

$$[(L_{15} + L'_0) \ggg 1] \oplus (H'_0 + L_1) - [(L_{15} + L_0) \ggg 1] \oplus (H_0 + L_1) = 0 \quad (9)$$

$$H'_0 - H_0 + \tilde{t}'_0 - \tilde{t}_0 = 0 \quad (10)$$

$$\tilde{t}'_0 \ggg 7 - \tilde{t}_0 \ggg 7 + (\tilde{t}'_0 \oplus H'_0) \ggg 13 - (\tilde{t}_0 \oplus H_0) \ggg 13 = 0 \quad (11)$$

Let us analyze (7). By fixing $L'_0 - L_0 = R$, and rotating to the left by 7 bits this equation can be rewritten as:

$$(X + A) \wedge C = X \wedge C + B \quad (12)$$

where $X = L_0, A = R, B = (-R) \lll 7, C = C_1$.

Now, let us analyze (8). Again, let us fix $L'_0 - L_0 = R$ and $H'_0 - H_0 = D$. Then (8) gets the following form:

$$(X + A) \vee C = X \vee C + B \quad (13)$$

where $X = H_0, A = D, B = R - (D \ggg 13), C = C_0$.

In (9), if we regroup the components, we get:

$$[(L_{15} + L'_0) \oplus (L_{15} + L_0)] \ggg 1 = (H'_0 + L_1) \oplus (H_0 + L_1)$$

Then, the above equation is of the following form:

$$((X + A) \oplus X) \ggg 1 = (Y + B) \oplus Y, \quad (14)$$

where $X = L_{15} + L_0, A = L'_0 - L_0, Y = L_1 + H_0, B = H'_0 - H_0$.

Now, let us analyze (10) and (11). Let us fix $H'_0 - H_0 = D$. Note that then from (10) we have $\tilde{t}'_0 - \tilde{t}_0 = -D$. If we rotate everything by 13 bits to the left in (11) we get:

$$(-D) \lll 6 + (\tilde{t}'_0 \oplus H'_0) - (\tilde{t}_0 \oplus H_0) = 0 \quad (15)$$

$$\tilde{t}_0 = [(\tilde{t}'_0 \oplus H'_0) - D \lll 6] \oplus H_0 \quad (16)$$

If we put this expression for \tilde{t}_0 in (10) we get:

$$D + \tilde{t}_0 - [(\tilde{t}_0 \oplus H'_0) - D \ll 6] \oplus H_0 = 0 \quad (17)$$

$$\tilde{t}_0 = [(\tilde{t}_0 \oplus H'_0) - D \ll 6] \oplus H_0 - D \quad (18)$$

If we XOR the value of H'_0 to the both sides:

$$\tilde{t}_0 \oplus H'_0 = ([(\tilde{t}_0 \oplus H'_0) - D \ll 6] \oplus H_0 - D) \oplus H'_0 \quad (19)$$

Let us denote $\tilde{t}_0 \oplus H'_0 = X$. Then we get:

$$X = [(X - D \ll 6) \oplus H_0 - D] \oplus H'_0 \quad (20)$$

$$X \oplus H'_0 = (X - D \ll 6) \oplus H_0 - D \quad (21)$$

Finally, we get an equation of the following form:

$$(X \oplus K_1) + A = (X + B) \oplus K_2 \quad (22)$$

where $K_1 = H'_0, A = R, B = -R \ll 6, K_2 = H_0$.

Lemma 2 *There exist efficient algorithms **Al1,Al2,Al3,Al4** for finding solutions for equations of type (12),(13),(14),(22).*

The description of these algorithms can be found in Appendix B.

Now, we can present our algorithm for finding solutions for the system of equations. With **Al1** we find a difference R (and values for L_0, L'_0) such that equation (7) holds. Actually, for the same difference R many different solutions (L_0, L'_0) exist (experimental results show that when (7) is solvable then there are around 2^5 solutions). Then, we pass as an input to **Al2** the difference R and we find a difference D (and values for H_0, H'_0) such that (8) holds. Again for a fixed R and D many (H_0, H'_0) exist. Experimentally for each random R and "good" D there are around 2^{10} solutions. Using **Al3** we check if we can find solutions for (9), i.e. we try to find L_1 and L_{15} . Notice, the input of **Al3** are the previously found L_0, L'_0, H_0, H'_0 . If **Al3** can not find a solution then we get another pair H_0, H'_0 (or generate first new difference D and then generate another 2^{10} pairs H_0, H'_0). If **Al3** finds a solution to (9), then with **Al4** we try to find solutions for (10),(11) where the input to **Al4** are already found H_0, H'_0 . If **Al4** can not find a solution, then we can take different pair H_0, H'_0 (or generate first new difference D and then generate H_0, H'_0) and then apply first **Al3** and then **Al4**.

4.2 Complexity of the Attack

Let us try to find the total complexity of the algorithm. Note that when analyzing the initial equations, we have used the assumption $(A + B) \gg r = (A \gg r) + (B \gg r)$, which holds with probability $\frac{1}{4}$ (see [6]). In total, we used

this assumption 5 times. In the equation for ΔF_0 we can control the exact value of M_1 , so in total we have used the assumption 4 times. Therefore the probability that a solution of the system is a solution for the initial equations is 2^{-8} . This means that we have to generate 2^8 solutions for the system. Let us find the cost for one solution.

The average complexity for both **A11** and **A12** is 2^1 . Experimentally, for a random difference R there exists a solution for (7) with probability 2^{-27} . So we can spend $2^{27} \cdot 2^1 = 2^{28}$ time and with **A11** we can find 2^5 solutions for (7). Similarly, for a random difference D , there is a solution for (8) with probability 2^{-27} . Therefore we can spend $2^{27} \cdot 2^1 = 2^{28}$ time and find 2^{10} pairs H_0, H_0 for (8). The probability that a pair is a good pair for (9) is 2^{-1} and that is a good pair for (10) and (11) is 2^{-12} (explained in Appendix B). Therefore we need $2^1 \cdot 2^{12} = 2^{13}$ pairs, which we can be generated in $2^{28} \cdot 2^3 = 2^{31}$ time. Since we need 2^8 solutions the total complexity is 2^{39} . Note that this complexity estimate is measured in the number of calls to the algorithms that solve our specific equations. If we assume that a call to the algorithms is four times less efficient then the call to the functions f or g (which on average seems to be true), and the fact that the compression function makes a total of around 2^8 calls to the functions f or g , we get that the total complexity of the collision search is around 2^{33} compression function calls.

Notice that when a solution for the system exists, then this still does not mean that we have a collision. This is partially because we cannot control some of the values directly. Indeed we can control directly only H_0, H'_0, t_0, t'_0 . The rest of the variables, i.e. L_0, L'_0, L_1, L_{15} , we will control through the message words M_i or with the input variables H_i , where $i > 0$. Since we pass these values as arguments for the non-injective function f we may experience situation when we can not get the exact value that we need. Yet, with overwhelming probability, we can find the exact values. Let us suppose we have a solution $(H_0, H'_0, L_0, L'_0, L_1, L_{15}, t_0, t'_0)$ for the system of equations. First we find a message word M_0 such that $f(F_{15}, H_0, M_0, C_0) = L_0$. Notice that F_{15} can be previously fixed by choosing some value for H_7 . Then $f(F_{15}, H'_0, M_0, C_0) = L'_0$. We choose M_1 such that $[M_1 + (L'_0 \wedge C_1)] \ggg 7 - [M_1 + (L_0 \wedge C_1)] \ggg 7 = (L'_0 \wedge C_1) \ggg 7 - (L_0 \wedge C_1) \ggg 7$. This way the probability the previous identity becomes 1. Then we find H_1 such that $f(L_0, H_1, M_1, C_1) = L_1$. At last, we find M_{15} such that $f(L_{14}, F_{15}, M_{15}, C_{15}) = L_{15}$. If such M_{15} does not exist, then we can change the value of L_{14} by changing M_{14} and then try to find M_{15} .

5 (H, S) -type Attack

The starting idea for this attack is to inject differences in the input chaining values H and salt S and then cancel them within the first iteration of `ProcessMessage`. Consequently, no difference appears throughout the compression function until the `FeedForward` step. If the differences in the chaining values and salt variables are selected appropriately, we can hope they cancel each other, so we get no difference at the output of the compression function.

5.1 Finding high-level differentials

To find a suitable differential for the attack, an approach similar to the one employed to analyse FORK-256 [10, Section 6] can be used. We model each of the registers a, b, c, d , as a single binary value $\delta a, \delta b, \delta c, \delta d$ that denotes whether there is a difference in the register or not. Moreover, we assume that we are able to make any two differences cancel each other to obtain a model that can be expressed in terms of arithmetics over \mathbb{F}_2 . We model the differential behavior of function g simply as $\delta g(\delta a, \delta b, \delta c, \delta d) = \delta a \oplus \delta b \oplus \delta c \oplus \delta d$, where $\delta a, \delta b, \delta c, \delta d \in \mathbb{F}_2$, as this description seems to be functionally closest to the original. For example, it is impossible to get collisions for g when only one variable has differences and such a model ensures that we always have two differences to cancel each other if we need no output difference of g . When deciding how to model $f(a, b, c, d)$, we have more options. First, note that when looking for collisions, there are no differences in message words and the last parameter of f is a constant, so we need to deal with differences in only two input variables a and b . Since we can find collisions for f when differences are only in a single variable (either a or b), we can model f not only as $\delta f(\delta a, \delta b) = \delta a \oplus \delta b$ but more generally as $\delta f(\delta a, \delta b) = \gamma_0(\delta a) \oplus \gamma_1(\delta b)$, where $\gamma_0, \gamma_1 \in \mathbb{F}_2$ are fixed parameters. Let us call the pair (γ_0, γ_1) a γ -configuration of δf and denote it by $\delta f_{[\gamma_0, \gamma_1]}$. As an example, $\delta f_{[1, 0]}$ corresponds to $\delta f(\delta a, \delta b) = \delta a$, which means that whenever a difference appears in register b , we need to use the properties of f to find collisions in the coordinate b . For functions f appearing in `FeedForward`, we use the model $\delta f = \delta a \oplus \delta b \oplus \delta c \oplus \delta d$.

With these assumptions, it is easy to see that such a model of the whole compression function is linear over \mathbb{F}_2 and finding the set of input differences (in chaining variables H_0, \dots, H_7 and salt registers S_0, \dots, S_3) is just a matter of finding the kernel of a linear map. Since we want to find only simple differentials, we are interested in those that use as few registers as possible. To find them, we can think of all possible states of the linear model as a set of codewords of a linear code over \mathbb{F}_2 . That way, finding differentials affecting only few registers corresponds to finding low-weight codewords. So instead of an enumeration of all 2^{12} possible states of $H_0, \dots, H_7, S_0, \dots, S_3$ for each γ -configuration of f functions, this can be done more efficiently by using tools like MAGMA [4].

We implemented this method in MAGMA and performed such a search for all possible γ -configurations of the 16 functions f appearing in the first `ProcessMessage`. We used the following search criteria: (a) as few active f functions as possible; (b) as few active g functions as possible; (c) non-zero differences appear only in the first few steps using function g as it is harder to adjust the values for later steps due to lack of variables we control; (d) we prefer γ -configurations $[1, 0]$ and $[0, 1]$ over $[1, 1]$ because it seems easier to deal with differences in one register than in two registers simultaneously.

The optimal differential for this set of criteria contains differences in registers $H_0, H_1, H_4, H_5, S_0, S_1$ with the following γ -configurations of the first seven f functions in `ProcessMessage`: $[0, 1], [1, 1], [0, 1], [\cdot, \cdot], [0, 1], [1, 1], [0, 1]$ (Note a simpler configuration (H_0, H_4, S_0) is not possible here). Unfortunately, the system

of constraints resulting from that differential has no solutions, so we introduced a small modification of it, adding differences in registers H_2, H_6, S_2 , ref. Figure 1. After introducing these additional differences, we gain more freedom at the expense of dealing with more active functions and we can find solutions for the system of constraints. The labels for all constraints are defined Figure 1, we will refer to them throughout the text.

```

SALTSTATE
input:  $H_0, \dots, H_7, S_0, \dots, S_3, t_0, t_1$ 
 $\Delta F_0 \leftarrow \Delta H_0$ 
 $\Delta F_1 \leftarrow \Delta H_1$ 
 $\Delta F_2 \leftarrow \Delta H_2$ 
 $F_3 \leftarrow H_3$ 
 $\Delta F_4 \leftarrow \Delta H_4$ 
 $\Delta F_5 \leftarrow \Delta H_5$ 
 $\Delta F_6 \leftarrow \Delta H_6$ 
 $F_7 \leftarrow H_7$ 
 $F_8 \leftarrow g(\Delta H_0, \Delta S_0 \oplus t_0, C_8, 0) \{s1\}$ 
 $F_9 \leftarrow g(\Delta H_1, \Delta S_1 \oplus t_1, C_9, 0) \{s2\}$ 
 $F_{10} \leftarrow g(\Delta H_2, \Delta S_2, C_{10}, 0) \{s3\}$ 
 $F_{11} \leftarrow g(H_3, S_3, C_{11}, 0)$ 
 $F_{12} \leftarrow g(\Delta H_4, \Delta S_0, C_{12}, 0) \{s4\}$ 
 $F_{13} \leftarrow g(\Delta H_5, \Delta S_1, C_{13}, 0) \{s5\}$ 
 $F_{14} \leftarrow g(\Delta H_6, \Delta S_2, C_{14}, 0) \{s6\}$ 
 $F_{15} \leftarrow g(H_7, S_3, C_{15}, 0)$ 
output:  $F_0, \dots, F_{15}$ 

FEEDFORWARD
input:  $R_0, \dots, R_{15}, H_0, \dots, H_7,$ 
 $S_0, \dots, S_3, t_0, t_1$ 
 $H_0 \leftarrow f(R_0, R_8, \Delta S_0 \oplus t_0, \Delta H_0) \{f1\}$ 
 $H_1 \leftarrow f(R_1, R_9, \Delta S_1 \oplus t_1, \Delta H_1) \{f2\}$ 
 $H_2 \leftarrow f(R_2, R_{10}, \Delta S_2, \Delta H_2) \{f3\}$ 
 $H_3 \leftarrow f(R_3, R_{11}, S_3, H_3)$ 
 $H_4 \leftarrow f(R_4, R_{12}, \Delta S_0, \Delta H_4) \{f4\}$ 
 $H_5 \leftarrow f(R_5, R_{13}, \Delta S_1, \Delta H_5) \{f5\}$ 
 $H_6 \leftarrow f(R_6, R_{14}, \Delta S_2, \Delta H_6) \{f6\}$ 
 $H_7 \leftarrow f(R_7, R_{15}, S_3, H_7)$ 
output:  $H_0, \dots, H_7$ 

PROCESSMESSAGE
input:  $F_0, \dots, F_{15}, M_0, \dots, M_{15}, \sigma$ 
 $L_0 \leftarrow f(F_{15}, \Delta F_0, M_{\sigma(0)}, C_0) \{p1\}$ 
 $\Delta L_1 \leftarrow f(L_0, \Delta F_1, M_{\sigma(1)}, C_1) \{p2\}$ 
 $\Delta L_2 \leftarrow f(\Delta L_1, \Delta F_2, M_{\sigma(2)}, C_2) \{p3\}$ 
 $L_3 \leftarrow f(\Delta L_2, F_3, M_{\sigma(3)}, C_3) \{p4\}$ 
 $L_4 \leftarrow f(L_3, \Delta F_4, M_{\sigma(4)}, C_4) \{p5\}$ 
 $\Delta L_5 \leftarrow f(L_4, \Delta F_5, M_{\sigma(5)}, C_5) \{p6\}$ 
 $\Delta L_6 \leftarrow f(\Delta L_5, \Delta F_6, M_{\sigma(6)}, C_6) \{p7\}$ 
 $L_7 \leftarrow f(\Delta L_6, F_7, M_{\sigma(7)}, C_7) \{p8\}$ 
 $L_8 \leftarrow f(L_7, F_8, M_{\sigma(8)}, C_8)$ 
 $\vdots$ 
 $L_{15} \leftarrow f(L_{14}, F_{15}, M_{\sigma(15)}, C_{15})$ 

 $W_0 \leftarrow g(L_{15}, L_0, \Delta F_0, \Delta L_1) \{p9\}$ 
 $W_1 \leftarrow g(W_0, \Delta L_1, \Delta F_1, \Delta L_2) \{p10\}$ 
 $W_2 \leftarrow g(W_1, \Delta L_2, \Delta F_2, L_3) \{p11\}$ 
 $W_3 \leftarrow g(W_2, L_3, F_3, L_4)$ 
 $W_4 \leftarrow g(W_3, L_4, \Delta F_4, \Delta L_5) \{p12\}$ 
 $W_5 \leftarrow g(W_4, \Delta L_5, \Delta F_5, \Delta L_6) \{p13\}$ 
 $W_6 \leftarrow g(W_5, \Delta L_6, \Delta F_6, L_7) \{p14\}$ 
 $W_7 \leftarrow g(W_6, L_7, F_7, L_8)$ 
 $\vdots$ 
 $W_{15} \leftarrow g(W_{14}, L_{15}, F_{15}, W_0)$ 
output:  $W_0, \dots, W_{15}$ 

```

Fig. 1. High-level differential used to look for (H, S) -type collisions

The process of finding the actual pair of inputs following the differential can be split into two phases. The first one is to solve the constraints from `ProcessMessage` to get the required F s (same as H s used in `SaltState`). Then, in the second phase, we look back at the `SaltState` to find appropriate salts to have constraints

in `FeedForward` satisfied. We can do this because the output from `ProcessMessage` has only a small effect on the solutions for `FeedForward`.

5.2 Solving the `ProcessMessage`

An important feature of our differentials in `ProcessMessage` is that it can be separated into two disjoint groups, i.e. $(F_0, F_1, F_2, L_1, L_2)$ and $(F_4, F_5, F_6, L_5, L_6)$. Differentials for these two groups have exactly the same structure. Thanks to that, if we can find values for the differences in the first group, we can reuse them for the second group by making corresponding registers in the second group equal to the ones from the first group. Following Observation 2 we can safely say that the second group also follows the differential path with a high probability. Algorithm 5 gives the details of solving the constraints in the first group of `ProcessMessage`.

- 1: Randomly pick $(L_2, L'_2) \in S_{fa}$
- 2: **repeat**
- 3: Randomly pick F_1 , compute $F'_1 = -1 - \Delta L_2 - F_1$
- 4: **until** $f_b(F_1) - f_b(F'_1) \in S_{fb_{odd}}^A$
- 5: **repeat**
- 6: Randomly pick L_1, F_2
- 7: Compute $L'_1 = f_b(F'_1) - f_b(F_1) + L_1$
- 8: Compute F'_2 so that $f_b(F'_2) = \Delta L_2 + f_a(L_1) - f_a(L'_1) + f_b(F_2)$
- 9: **until** $p11$ is fulfilled
- 10: Pick $(F_0, F'_0) \in S_{fb}$ so that $\Delta F_0 + \Delta L_1 = 0$

Algorithm 5: Find solutions for the first group of differences of `ProcessMessage`

Correctness We show that after the execution of Algorithm 5, it indeed finds values conforming to the differential. In other words, we show that constraints $p1 - p4$ and $p9 - p11$ hold. Referring to Algorithm 5:

- Line 1: (L_2, L'_2) is chosen in such a way that $p4$ is satisfied.
- Line 3: F'_1 is computed in such a way that $(F_1 + L_2) \oplus (F'_1 + L'_2) = -1$
- Line 4: $\Delta L_1 = \Delta f_b(F_1)$ is odd together with $(F_1 + L_2) \oplus (F'_1 + L'_2) = -1$. This implies that $p10$ could hold, which will be discussed later in Lemma 3. The fact that $\Delta L_1 \in S_{fb_{odd}}^A$ makes it possible that $p1$ and $p9$ hold.
- Line 7: L'_1 is computed in such a way that $p2$ holds.
- Line 8: F'_2 is computed in such a way that $p3$ holds.
- Line 9: after exiting the loop $p11$ holds.
- Line 10: (F_0, F'_0) is chosen in such a way that $p1, p9$ hold.

Probability and Complexity Analysis Let us consider the probability for exiting the loops in Algorithm 5. We require $f_a(F_1) - f_a(F'_1) \in S_{fb_{odd}}^A$ and the constraint $p11$ to hold. The size of the set $S_{fb_{odd}}^A$ is around 2^{11} . By assuming that $f_a(F_1) - f_a(F'_1)$ is random, the probability to have it in $S_{fb_{odd}}^A$ is 2^{-21} . This needs to be done only once. Now we show that the constraint $p11$ is satisfied with the probability 2^{-24} . We have sufficiently many choices, i.e. 2^{64} , for (L_1, F_2) to have $p11$ satisfied. The constraint $p11$ requires that $[(W_1 + L_2) \ggg 1] \oplus (F_2 + L_3) = [(W_1 + L'_2) \ggg 1] \oplus (F'_2 + L_3)$, which is equivalent to $[(W_1 + L_2) \oplus (W_1 + L'_2)] \ggg 1 = (F_2 + L_3) \oplus (F'_2 + L_3)$, where $W_1, L_2, L'_2, F_2, F'_2$ are given from previous steps. We have choices for L_3 by choosing an appropriate $M_{\sigma(3)}$. The problem could be rephrased as follows: *given random A and D , what is the probability to have at least one x such that $x \oplus (x + D) = A$?*

To answer this question, let us note first that $x \oplus y = (1, \dots, 1)$ iff $x + y = -1$. This is clear as $y = \bar{x}$ and always $(x \oplus \bar{x}) + 1 = 0$. Now we can show the following result.

Lemma 3 *For any odd integer d , there exist exactly two x such that $x \oplus (x + d) = (1, \dots, 1)$. They are given by $x = (-1 - d)/2$ and $x = (-1 - d)/2 + 2^{n-1}$.*

Proof. $x \oplus (x + d) = -1$ implies that $x + x + d = -1 + k2^n$ for an integer k , so $x = \frac{-1-d+k2^n}{2}$. Only when d is odd, $x = \frac{-1-d}{2} + k2^{n-1}$ an integer and a solution exists. As we are working in modulo 2^n , $k = 0, 1$ are the only solutions. \square

Following the lemma, given an odd ΔL_1 and $(F_1 + L_2) \oplus (F'_1 + L'_2) = -1$, we can always find two W_0 such that $(W_0 + L_1) \oplus (W_0 + L'_1) = -1$, then $p10$ follows. Such W_0 could be found by choosing an appropriate L_{15} which could be adjusted by choosing $M_{\sigma(15)}$ (if such $M_{\sigma(15)}$ does not exist, although the chance is low, we can adjust L_{14} by choosing $M_{\sigma(14)}$).

Coming back to the original question, consider A as “0”s and blocks of “1”s. Following the lemma above, for $A_i = 0$, we need $D_i = 0$ (except “0” as MSB followed by a “1”); for a block of “1”s, say $A_k = A_{k+1} = \dots = A_{k+l} = 1$, the condition that needs to be imposed on D is $D_k = 1$. By counting the number of “0”s and the number of blocks of “1”s, we can get number of conditions needed. For an n -bit A , the number is $\frac{3n}{4}$ on average (cf. Appendix Lemma 4).

For LAKE-256, it is 24, so the probability for $p11$ to hold is 2^{-24} . We will need to find the appropriate L_3 so that $p11$ holds. Note we have control over L_3 by choosing the appropriate $M_{\sigma(3)}$. For each differential path found, we need to find message words fulfilling the path. The probability to find a correct message is $1 - \frac{1}{e}$ for the first path by assuming f_c is random (because for a random function from n bits to n bits the probability that a point from the range has a preimage is $1 - \frac{1}{e}$), and $\frac{4}{9}$ for second path because of the carry effect. For example, given L_0, F_{15}, F_0, C_0 , the probability to have $M_{\sigma(0)}$ so that $L_0 = f(F_{15}, F_0, M_{\sigma(0)}, C_0)$ is $1 - \frac{1}{e}$. The same $M_{\sigma(0)}$ satisfies $L'_0 = f(F'_{15}, F'_0, M_{\sigma(0)}, C_0)$ (note for this case $F'_{15} = F_{15}$ and $L_0 = L'_0$) is $\frac{4}{9}$. So for each message word, the probability for it to fulfill the differential path is 2^{-2} . We have such restrictions on $M_{\sigma(0)} - M_{\sigma(2)}, M_{\sigma(4)} - M_{\sigma(6)}$ (we don't have such restriction on $M_{\sigma(3)}$ and $M_{\sigma(7)}$

because we still have control over F_3 and F_7), so overall complexity for solving `ProcessMessage` is $5 \cdot 2^{36}$ in terms of calls to f_a or f_b . The compression function of LAKE-256 calls functions f and g 136 times each and f_a, f_b contain less than half of the operations used in f . So the complexity for this part of the attack is 2^{30} in terms of the number of calls to the compression function.

Solving the second group of `ProcessMessage` After we are done with the first group, we can have the second group of differential path for free by assigning $F_{i+4} = F_i, F'_{i+4} = F'_i$ for $i = 0, 1, 2$ and $L_{i+4} = L_i, L'_{i+4} = L'_i$ for $i = 1, 2$. In this way, we can have $p5-p8$ and $p12$ automatically satisfied. Similarly, for constraint $p13$ and $p14$, we will need appropriate W_4 and L_7 . We have control over W_4 by choosing F_3 and L_4 (note we need to keep L_3 stable to have $p11$ satisfied, this can be achieved by choosing appropriate $M_{\sigma(3)}$). We also have control over L_7 by choosing $M_{\sigma(7)}$. That way we can force the difference to vanish within the first `ProcessMessage`. Table 2 in Appendix shows an example of a set of solutions.

5.3 Near collisions

In this section we explain how to get a near collision directly from collisions of `ProcessMessage`. Refer to `SaltState` and `FeedForward` in Fig. 1. Note that the function $g(a, b, c, d)$ with differences at positions (a, b) means $\Delta a + \Delta b = 0$, then constraints ($s1 - s6$) in `SaltState` can be simplified to:

$$s1 : \Delta H_0 + \Delta S_0 = 0 \quad (23)$$

$$s2 : \Delta H_1 + \Delta S_1 = 0 \quad (24)$$

$$s3 : \Delta H_2 + \Delta S_2 = 0 \quad (25)$$

Note that $H_{i+4} = H_i, H'_{i+4} = H'_i$ for $i = 0, 1, 2$ as required by `ProcessMessage`. Let $t_0 = t_1 = 0$, then conditions $s4 - s6$ follow $s1 - s3$. Conditions in `FeedForward` could be simplified to:

$$f1 : f_{cd}(S_0, H_0) = f_{cd}(S'_0, H'_0) \quad (26)$$

$$f2 : f_{cd}(S_1, H_1) = f_{cd}(S'_1, H'_1) \quad (27)$$

$$f3 : f_{cd}(S_2, H_2) = f_{cd}(S'_2, H'_2) \quad (28)$$

and $f4 - f6$ follow $f1 - f3$. This set of constraints can be grouped into three independent sets (s_i, f_i) for $i = 0, 1, 2$ each one of the same type, i.e. $\Delta H + \Delta S = 0$ and $f_{cd}(S, H) = f_{cd}(S', H')$.

To find near collisions, we proceed as follows. First we choose those S_i with $S'_i = S_i - \Delta H_i$ so that the Hamming weight of $f_{cd}(S'_i, H'_i) - f_{cd}(S_i, H_i)$ is small for $i = 0, 1, 2$. Thanks to that, only small differences are expected in the final output of the compression function, due to the fact that inputs from a, b of function f have only carry effect to the final difference of f when inputs differ in c, d only. We choose values of S_i without going through the compression function, so the number of rounds of the compression function does not affect our algorithm.

Further, the complexity for finding values of S_i is much smaller than that of `ProcessMessage`, so it does not increase the 2^{30} complexity. Experiments show that, based on the collision in `ProcessMessage`, we can have near collisions with very little additional effort. Table 3 in Appendix shows a sample result with 16-bit of differences out of 256 bits of output.

5.4 Extending the attack to full collisions

It is clear that finding full collisions is equivalent to solving equations (26)-(28). The complexity to solve a single equation is around 2^{12} (as done for solving equations (10) and (11)). Looking at Algorithm 5, $(s1, f1)$ can be checked when F_1 and F'_1 are chosen, so it does not affect the overall complexity. The pair $(s0, f0)$ can be checked immediately after (L_1, L'_1) is given as show in Line 7 of Algorithm 5. Similarly, $(s2, f2)$ can be checked after (F_2, F'_2) is chosen in Line 8. So the overall complexity for our algorithm to get a collision for the full compression function is 2^{54} .

5.5 Reducing the Complexity

In this subsection, we show a better way (rather than randomly) to choose (L_2, L'_2) so that the probability for the constraint $p11$ to hold increases, which reduces the complexity for collision finding to 2^{42} .

Note the constraint $p11$ is as follows: given W_1, L_2, L'_2 , what is the probability to have L_3 and (F_2, F'_2) so that $((W_1 + L_2) \oplus (W_1 + L'_2)) \ggg 1 = (F_2 + L_3) \oplus (F'_2 + L_3)$. We calculate the probability by counting the number of 0s and block of 1s in $((W_1 + L_2) \oplus (W_1 + L'_2)) \ggg 1$ (let's denote it as $\alpha = \#(((W_1 + L_2) \oplus (W_1 + L'_2)) \ggg 1)$). Now we show that the number α can be reduced within the first loop of the algorithm, i.e. given only (L_2, L'_2) and (F_1, F'_1) , we are able to get the count α and hence, by repeating the loop sufficiently many times, we can reduce the count α to a certain number less than 24 (we don't fix it here, but will give it later).

Note that to find α , we still need W_1 besides (L_2, L'_2) . Now we show W_1 can be computed from (L_2, L'_2) and (F_1, F'_1) only. $W_1 \stackrel{\text{def}}{=} ((W_0 + L_1) \ggg 1) \oplus (F_1 + L_2)$, where we restrict $(W_0 + L_1) \oplus (W_0 + L'_1) = -1$. Denote $S = (W_0 + L_1)$, then the equation can be derived to $S \oplus (S + \Delta L_1) = -1$, where $\Delta L_1 \stackrel{\text{def}}{=} f_b(F'_1) - f_b(F_1)$.

So let's make 2^y more effort in the first loop so that α is reduced by y . The probability for first loop to exit becomes 2^{-33-y} and for the second loop, the probability becomes 2^{-60+y} . Choosing the optimal value $y = 13$ (y must be an integer), the probabilities are 2^{-46} and 2^{-47} , respectively. Hence this gives final complexity 2^{42} for collision searching.

6 (H)-type Attack

Let us introduce difference only in the chaining value H_0 . Hence, this difference after the `SaltState` procedure, will produce differences in F_0 and F_8 . In the first application of the `ProcessMessage` procedure the following differential is used:

1. Let F_0 has some specially chosen difference. Also, F_8 has some difference that depends on the difference in F_0 .
2. After the first application of the function f only L_0, L_1, \dots, L_8 have non-zero differences
3. After the first application of the function g all W_i have zero differences

Again, we should prove that this differential is possible. Basically, we should check only for the updates with non-zero input differences and zero output difference (other updates hold trivially). Hence, we should prove that we can get zero difference in L_9 and $W_i, i = 0, \dots, 8$. Since f is non-injective it is possible to get a zero difference in L_9 . For W_0, \dots, W_8 is also possible to get zero differences because their updating functions g always have at least two arguments with differences. Therefore, this differential is valid.

Now, let us write the system of equations that we require. Note that $L_i - L'_i = \delta_i, i = 0, \dots, 8$.

$$f(F_{15}, L_0, M_0, C_0) = L_0, f(F_{15}, L'_0, M_0, C_0) = L'_0 \quad (29)$$

$$f(L_0, F_1, M_1, C_1) = L_1, f(L'_0, F_1, M_1, C_1) = L'_1 \quad (30)$$

$$f(L_{i-1}, F_i, M_i, C_i) = L_i, f(L'_{i-1}, F_i, M_i, C_i) = L'_i, i = 2, \dots, 6, \quad (31)$$

$$f(L_7, L_8, M_8, C_9) = L_8, f(L_7, L'_8, M_8, C_9) = L'_8 \quad (32)$$

$$f(L_8, F_9, M_9, C_9) = L_9, f(L'_8, F_9, M_9, C_9) = L_9 \quad (33)$$

$$g(L_{15}, L_0, F_0, L_1) = W_0, g(L_{15}, L'_0, F'_0, L'_1) = W_0 \quad (34)$$

$$g(W_{i-1}, L_i, F_i, L_{i+1}) = W_i, g(W_{i-1}, L'_i, F_i, L'_{i+1}) = W_i, i = 1, \dots, 7 \quad (35)$$

$$g(W_7, L_8, L_8, L_9) = g(W_7, L'_8, L'_8, L_9) \quad (36)$$

Let us focus on (35). This equation can be rewritten as:

$$(W_{i-1} + L_i) \ggg 1 \oplus (F_i + L_{i+1}) = (W_{i-1} + L'_i) \ggg 1 \oplus (F_i + L'_{i+1}) \quad (= W_i)$$

Similarly as in the previous attacks, we get the following equation:

$$((X + A) \oplus X) \ggg 1 = (Y + B) \oplus Y, \quad (37)$$

where $X = W_{i-1} + L'_i, A = L_i - L'_i, Y = F_i + L'_{i+1}, B = L_{i+1} - L'_{i+1}$. In **A13** of Appendix B, we have explained how to split this equation into two equations, $((X + A) \oplus X) = -1, (Y + B) \oplus Y = -1$, and solve them separately. The solution $X = \overline{A \ggg 1}, Y = \overline{B \ggg 1}$ exists when LSB of A and B are 1. Hence, for W_{i-1} and F_i we get:

$$W_{i-1} = \overline{(L_i - L'_i) \ggg 1 - L'_i} = \overline{\delta_i \ggg 1} - L'_i \quad (38)$$

$$F_i = \overline{(L_{i+1} - L'_{i+1}) \ggg 1 - L'_{i+1}} = \overline{\delta_{i+1} \ggg 1} - L'_{i+1} \quad (39)$$

If we put these values in the equation for W_i we get:

$$W_i = (W_{i-1} + L'_i) \ggg 1 \oplus (F_i + L'_{i+1}) = \overline{\delta_i \ggg 1} \ggg 1 \oplus \overline{\delta_{i+1} \ggg 1} \quad (40)$$

This means that we can split the equations of type (35) into two equations and solve them separately. Also, from (38) and (39) we get that $W_i = F_i$.

Now let us explain how to get two pairs that satisfy the whole differential. First, by choosing randomly $L_0, L'_0, F_{15}, M_0, F_1$, and M_1 , we produce a solution for the equations (29),(30), (34) and the split (35). Actually, we need to satisfy only the split (35), i.e. $W_0 = \overline{(L_1 - L'_1)} \gg 1 - L'_1 = \overline{\delta_1} \gg 1 - L'_1$, because the values of $L_0^j, L_1^j, j = 1, 2$ can be any, and finding a solution for (34) is trivial. Then, by taking some M_2 and F_2 we produces $L_2^j = f(L_1^j, F_2, M_2, C_2), j = 1, 2$. Having the values of δ_1 and δ_2 we can find the new value of F_1 :

$$F_1 = W_1 = \overline{\delta_1} \gg 1 \gg 1 \oplus \overline{\delta_2} \gg 1$$

Since we have changed the value of F_1 , then the values of L_1 and L'_1 might change. Therefore, we find another value of M_1 such that the old values of L_1, L'_1 stay the same. Note, that is is not always possible. Yet, with probability 2^{-2} this value can be found. As a result, we have fixed the values of M_1, F_1, L_2 , and L'_2 . Using the same technique, we can fix the values of $M_2, \dots, M_6, F_2, F_6, L_3^j, L_7^j, j = 1, 2$ such that (35) would hold for $i = 2, \dots, 6$. In short, the following is done. Let the values of W_{i-1}, M_i, F_i, L_i , and L'_i be fixed. First we generate any L_{i+1} and L'_{i+1} . Then we find the value of F_i from (39). Then, we change the value of M_i . This way, the values of L_i, L'_i stay the same, but now $W_{i+1}, L_i^j, M_i, F_i, L_{i+1}^j, j = 1, 2$ satisfy (35).

Now let us fix the right L_8, L'_8 such that:

$$f(L_8, F_9, M_9, C_9) = f(L'_8, F_9, M_9, C_9) \quad (41)$$

We try different M_8, S_0 (notice that the values of F_8, F'_8 depend on F_0, F'_0 , and S_0), and create different pairs (L_8, L'_8) . If this pair satisfies (41) and (38) then we change M_7 and F_7 as described previously. Finally, we change M_9 and F_9 so that (36) will hold. First, we find the good value of L_9 from the equation $L_9 = \overline{\Delta_2} \gg 1 - L'_8$ and than change M_9 and F_9 to achieve this value. As a result, we have fixed all the values such that all equations hold.

After the `ProcessMessage` procedure, there are no differences in any of the state variables. The `FeedForward` procedure, which produces the new chaining value, depends on the initial chaining value, the internal state variables, the salt, and the block index. Since there is difference only in the initial chaining value (only in H_0), it means that there has to be a difference in the new chaining value H_0 (and only there). If we repeat the attack on `ProcessMessage` with different input difference Δ_1 , we can produce a near collision with a low Hamming difference. If, in the truncated digest LAKE-224, the first 32 bits were truncated instead of the last 32 bits, we could find a real collisions for the compression function of LAKE-224.

Now, let us estimate the complexity of attack. For finding good random $L_0, L'_0, F_{15}, M_0, F_1$, and M_1 that satisfies the first set of equations we have to try 2^{32} different values. For successfully fixing the correct $F_i, M_i, i = 1, \dots, 7$, we have to start with $(2^2)^7 = 2^{14}$ different δ_1 . For finding a good pair (L_8, L'_8)

that satisfies (41) and (38) we have to try $2^{27} \cdot 2^{32} = 2^{59}$ different M_8, S_8 . Hence, the total attack complexity is around 2^{105} computations. If we apply the same reasoning for computing the complexity in the number of compression function calls as it was done in the two previous attacks, we will get that the near collision algorithm requires around 2^{99} calls to the compression function of LAKE-256.

7 Conclusions

We presented three different collision attacks on the compression function of LAKE-256. All of them make use of some undesirable properties of the functions used to build the compression function. The first two of them facilitate the additional variables of salt and block counter required by the HAIFA compression functions. Due to a weaker mixing of those variables, we were able to better control the differences contained in them.

All our attacks cancel the injected differences within the first `ProcessMessage` and later only in the final `FeedForward` again and therefore are independent of the number of rounds.

The SHA-3 first round candidate BLAKE, a successor of LAKE, uses a different `ProcessMessage` function. Hence, our attacks do not apply to BLAKE. We believe that the efficient methods to solve the systems of equations and to find high level differentials presented in this paper may be useful to analyse other dedicated designs based on modular additions, rotations and XORs and constitute a nice illustration of how very small structural weaknesses can lead to attacks on complete designs.

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Table 1. (H, t) -colliding pair for the compression function of LAKE

h_0	63809228 6cc286da 00000000 00000000 00000000 00000000 00000000 00000540
h'_0	ba3f5d77 6cc286da 00000000 00000000 00000000 00000000 00000000 00000540
M	55e07658 00000009 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000002 5c41ab0e
F_0	0265e384 00000000
F_1	aba71835 00000000
S	00000000 00000000 00000000 00000000
H	79725351 e61a903f 730aace9 756be78a b679b09d de58951b f5162345 14113165

Table 2. Example of a pair of chaining values F, F' and a message block M that yield a collision in ProcessMessage

F	1E802CB8 799491C5 1FE58A14 07069BED 1E802CB8 799491C5 1FE58A14 74B26C5B 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
F'	C0030007 B767CE5E 30485AE7 07069BED C0030007 B767CE5E 30485AE7 74B26C5B 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
M	683E64F1 9B0FC4D9 0E36999A A9423F09 27C2895E 1B76972D BEF24B1C 78F25F25 00000000 00000000 00000000 00000000 00000000 00000000 657C34F5 3A992294
L	DOF3077A 31A06494 395A0001 10E105FC 82026885 31A06494 395A0001 10E105FC ECF7389A 2F4D466F 9FFC71E1 54BAFAE6 FCDDBCDB E635FFB7 5D302719 CD102144
L'	DOF3077A 901D9145 95A99FDB 10E105FC 82026885 901D9145 95A99FDB 10E105FC ECF7389A 2F4D466F 9FFC71E1 54BAFAE6 FCDDBCDB E635FFB7 5D302719 CD102144
L^\oplus	00000000 A1BDF5D1 ACF39FDA 00000000 00000000 A1BDF5D1 ACF39FDA 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
W	1F210513 1A8E2515 1932829B 1C00C039 1F210513 1A8E2515 1932829B F4A060BE 5F868AC3 D8959978 E8F3FF4A E20AC1C3 8941C0F8 EA8BC74E 6ECDD677 82CFE9CE
W'	1F210513 1A8E2515 1932829B 1C00C039 1F210513 1A8E2515 1932829B F4A060BE 5F868AC3 D8959978 E8F3FF4A E20AC1C3 8941C0F8 EA8BC74E 6ECDD677 82CFE9CE

Table 3. Example of a pair of chaining values F, F' , salts S, S' and a message block M that yield near collision in CompressionFunction with 16 bits differences out of 256 bits output. H_s are final output.

F	7B2000C4 23E79FBD 73D102C3 88E0E02B 7B2000C4 23E79FBD 73D102C3 00000000
F'	801FF801 18C0005E 846FD480 88E0E02B 801FF801 18C0005E 846FD480 00000000
S	00010081 23043423 03C5B03E D44CFD2C
S'	FB010944 2E2BD382 F326DE81 D44CFD2C
M	00000012 64B31375 CFA0A77E 8F7BE61F 1E30C9D3 6A9FB0DA 290E506E 3AAE159C 00000000 00000000 00000000 00000000 00000000 00000000 00000000 1B89AA75
H	261B50AA 3873E2BE BDD7EC4D 7CE4BFF8 007BB4D4 869473FF 833D9EFA 9DABEDDA
H'	361150AA 387BE23E FDD6E84D 7CE4BFF8 1071B4D4 869C737F C33C9AFA 9DABEDDA
H^\oplus	100A0000 00080080 40010400 00000000 100A0000 00080080 40010400 00000000

A Collision Examples

B Lemmas and proofs

Lemma 4 Given random x of length n , then the average number of “0”s and block of “1”s, excluding the case “0” as MSB followed by “1”, is $\frac{3n}{4}$.

Proof. Denote C_n as the sum of the counts for “0”s and blocks of “1”s for all x of length n , denote such x as x_n . Similarly we define P_n as the sum of the counts for all x of length n with MSB “0” (let’s denote such x as x_n^0); and Q_n for the sum of the counts for all x of length n with MSB “1” (denote such x as x_n). It is clearly that

$$C_n = P_n + Q_n \quad (42)$$

Note that there are 2^{n-1} many x with length $n-1$, half of them with MSB “0”, which contribute to P_{n-1} and the other half with MSB “1”, which contribute to Q_{n-1} . Now we construct x_n of length n from x_{n-1} of length $n-1$ in the following way:

- Append “0” with each x_{n-1} , this “0” contribute to C_n once for each x_{n-1} and there are 2^{n-2} many such x_{n-1} .
- Append “1” with each x_{n-1} , this “1” does not contribute to C_n
- Append “0” with each x_{n-1}^0 , this contributes 2^{n-2} to C_n
- Append “1” with each x_{n-1}^0 , this contributes 2^{n-2} to C_n

So overall we have $C_n = P_{n-1} + P_{n-1} + 2^{n-2} + Q_{n-1} + 2^{n-2} + Q_{n-1} + 2^{n-2} = 3 \cdot 2^{n-2} + 2C_{n-1}$. Note $C_1 = 2$, solving the recursion, we get $C_n = \frac{3n+1}{4} \cdot 2^n$. Exclude the exceptional case, we have final result $\frac{3n}{4}$ on average.

Lemma 5 *Given random $a, a', x \in \mathbb{Z}_{2^n}$ and $k \in [0, n)$, $\alpha \stackrel{\text{def}}{=} \mathbf{1}[a_k^L + x_k^L \geq 2^k], \alpha' \stackrel{\text{def}}{=} \mathbf{1}[a_k^L + x_k^L \geq 2^k], \beta \stackrel{\text{def}}{=} \mathbf{1}[a_k^R + x_k^R + \alpha \geq 2^{n-k}], \beta' \stackrel{\text{def}}{=} \mathbf{1}[a_k^R + x_k^R + \alpha \geq 2^{n-k}]$ as defined in Lemma 1, then $P(\alpha = \alpha', \beta = \beta') = \frac{4}{9}$.*

Proof. Consider α and α' first, $P(\alpha = \alpha' = 1) = P(a_k^L + x_k^L \geq 2^k, a_k^L + x_k^L \geq 2^k)$. This is equal to $P(x_k^L \geq (2^k - \min\{a_k^L, a_k^L\}))$ what in turns can be rewritten as $P(a_k^L \geq a_k^L)P(x_k^L \geq 2^k - a_k^L) + P(a_k^L > a_k^L)P(x_k^L \geq 2^k - a_k^L) = \frac{1}{2} \cdot \frac{1}{3} + \frac{1}{2} \cdot \frac{1}{3} = \frac{1}{3}$.

Similarly we can prove $P(\alpha = \alpha' = 0) = \frac{1}{3}$, so $P(\alpha = \alpha') = \frac{2}{3}$. Note the definitions of β and β' contain α and α' , but $\alpha, \alpha' \in \{0, 1\}$, which is generally much smaller than 2^{n-k} , so the effect of α to β is negligible. We can roughly say $P(\beta = \beta') = \frac{2}{3}$. So $P(\alpha = \alpha', \beta = \beta') = P(\alpha = \alpha')P(\beta = \beta') = \frac{4}{9}$.

Lemma 6 *There exist an algorithm (A1) for finding all the solutions for the equation of the form $(X \wedge C) + A = (X + B) \wedge C$. The complexity of A1 depends only on the constant C .*

Lemma 7 *There exist an algorithm (A2) for finding all the solutions for the equation of the form $(X \vee C) + A = (X + B) \vee C$. The complexity of A2 depends only on the constant C .*

Proof. The proofs for the two facts are very similar with some minor changes, so we will prove only Lemma 6.

Let $X = x_{31} \dots x_1 x_0, A = a_{31} \dots a_1 a_0, B = b_{31} \dots b_1 b_0, C = c_{31} \dots c_1 c_0$. Then for each i we have:

$$(x_i \wedge c_i) \oplus a_i \oplus F_i = (x_i \oplus b_i \oplus r_i) \wedge c_i, \quad (43)$$

where $F_i = m(x_{i-1} \wedge c_{i-1}, a_{i-1}, F_{i-1})$ is the carry at the $(i-1)$ th position of $(X \wedge C + A)$, $r_i = m(x_{i-1}, b_{i-1}, r_{i-1})$ is the carry at the $(i-1)$ th position of $X + B$, and $m(x, y, z) = xy \oplus xz \oplus yz$.

Equation (43), simplifies to $a_i \oplus F_i = 0$ when $c_i = 0$ and when $c_i = 1$ we get $a_i \oplus F_i = b_i \oplus r_i$.

Let us assume that we have found the values for F_i and r_i for some i . We find the smallest $j > 0$ such that $c_{i+j} = 0$. Then from the fact that $a_i \oplus F_i = 0$ and the definition of F_i we get:

$$\begin{aligned} a_{i+j} = F_{i+j} &= m(x_{i+j-1}, a_{i+j-1}, F_{i+j-1}) = \\ &= m(x_{i+j-1}, a_{i+j-1}, m(x_{i+j-2}, a_{i+j-2}, F_{i+j-2})) = \dots \\ &= m(x_{i+j-1}, a_{i+j-1}, m(x_{i+j-2}, a_{i+j-2}, m(\dots, m(x_i, a_i, F_i)) \dots)) \end{aligned}$$

In the above equation, only $x_i, x_{i+1}, \dots, x_{i+j-1}$ are unknown. So we can try all the possibilities, which are 2^j , and find all the solutions. Let us denote by \tilde{X} the set of all solutions.

Now, let us find the smallest $l > 0$ such that $c_{i+j+l} = 1$. Notice that we can easily find F_{i+j+1} if considering $c_{i+j+F_0} = 0$ for $F_0 \in (0, l)$ and using $a_i \oplus F_i = 0$:

$$\begin{aligned} F_{i+j+1} &= m(0, a_{i+j}, F_{i+j}) = m(0, a_{i+j}, a_{i+j}) = a_{i+j} \\ F_{i+j+2} &= m(0, a_{i+j+1}, F_{i+j+1}) = m(0, F_{i+j+1}, F_{i+j+1}) = m(0, a_{i+j}, a_{i+j}) = a_{i+j} \\ &\dots \\ F_{i+j+l} &= m(0, a_{i+j+l-1}, F_{i+j+l-1}) = a_{i+j} \end{aligned}$$

From the relationship $a_i \oplus F_i = b_i \oplus r_i$ and definition of r_i we get:

$$\begin{aligned} a_{i+j+l} \oplus F_{i+j+l} \oplus b_{i+j+l} &= r_{i+j+l} = m(x_{i+j+l-1}, b_{i+j+l-1}, r_{i+j+l-1}) = \\ &= m(x_{i+j+l-1}, b_{i+j+l-1}, m(x_{i+j+l-2}, b_{i+j+l-2}, r_{i+j+l-2})) = \dots \\ &= m(x_{i+j+l-1}, b_{i+j+l-1}, m(\dots, m(x_i, b_i, r_i) \dots)) \end{aligned}$$

In the above equation, only $x_i, x_{i+1}, \dots, x_{i+j+l-1}$ are unknown. So we check all the possibilities by taking $(x_i, x_{i+1}, \dots, x_{i+j-1})$ from the set \tilde{X} and the rest of the variables take all the possible values. If the equation has a solution, then this means we have fixed another F_{i+j+l} , r_{i+j+l} , and we can continue searching using the same algorithm.

The complexity of the algorithms is 2^q , where q is size of the longest consecutive sequence of ones followed by consecutive zero sequence (in the case above $q = j + l$) in the constant C . Taking into consideration the value of the constant C_1 used in the compression function of LAKE-256, we get that complexity of our algorithm for this special case is 2^8 . Yet, the average complexity can be decreased additionally if first the necessary conditions are checked. For example, if we have two consecutive zeros in the constant C_1 at positions i and $i+1$ then it has to hold $a_{i+1} = a_i$. If we check for all zeros, then only with probability of 2^{-10} a constant A can pass this sieve. Therefore, the math expectancy of the complexity for a random A is less than 2^1 . Note that when \vee function is used

instead of \wedge , than 0 and 1 change place. Therefore, our algorithm has a complexity of 2^6 when C_0 is used as a constant. Yet, same as for \wedge , early break-up strategies significantly decrease these complexities for the case when solution does not exist. Again, the average complexity is less than 2^1 . \square

Lemma 8 *There exist an algorithm (A13) for finding a solution for the following equation: $((X + A) \oplus X) \gg 1 = (Y + B) \oplus Y$.*

Proof. Instead of finding a solution w.r.t. X and Y we split the equation into a system

$$(X + A) \oplus X = -1, \quad (Y + B) \oplus Y = -1 . \quad (44)$$

We can do this because the value of -1 is invariant of any rotation. We may loose some solutions, but further we will prove that if such a solution exist then our algorithm will find it with probability 2^{-2} .

We will analyze only left equation of (44); the second one can be solved analogously. Let $X = x_{31} \dots x_0, A = a_{31} \dots a_0$. Then for i th bit we get: $(x_i \oplus a_i \oplus c_i) \oplus x_i = 1$, where c_i is the carry at $(i - 1)$ position of $X + A$, i.e. $c_i = m(x_{i-1}, a_{i-1}, c_{i-1})$. Obviously, this equation can be rewritten as $a_i = c_i \oplus 1$. For the $(i + 1)$ th bit we get $a_{i+1} = c_{i+1} \oplus 1 = m(x_i, a_i, c_i) \oplus 1 = m(x_i, a_i, a_i \oplus 1) \oplus 1 = x_i a_i \oplus x_i (a_i \oplus 1) \oplus a_i (a_i \oplus 1) \oplus 1 = x_i \oplus 1$. So, we can easily find the value of x_i for each i . When $i = 31$, x_{31} can be arbitrary. For the case when $i = 0$, considering that $c_0 = 0$, from $a_i = c_i \oplus 1$ we get $a_0 = 1$. Therefore, if $a_0 = 1$ then (44) is solvable in constant time. The solutions are $X = \bar{A} \gg 1 + i2^{32}, i = 0, 1$. Finally, for the whole system, we have that solution exist if $a_0 = b_0 = 1$, which means with probability 2^{-2} . \square

Lemma 9 *There exists an algorithm (A14) for finding all the solutions for equations of the type $(X \oplus C) + A = (X + B) \oplus K$.*

Proof. We base our algorithm fully on the results of [14]. There, Paul and Preneel show, in particular, how to solve equations of the form: $(x + y) \oplus ((x \oplus \alpha) + (y \oplus \beta)) = \gamma$. Let us XOR to the both sides of the initial equation the expression $A \oplus B \oplus C$ and denote $\tilde{K} = K \oplus A \oplus B \oplus C$. Then, the equation gets the following form: $((X \oplus C) + A) \oplus A \oplus B \oplus C = (X + B) \oplus \tilde{K}$. For the $(i + 1)$ th bit position, we have $\tilde{k}_{i+1} = s_{i+1} \oplus F_{i+1}$, where s_i is the carry at the i th position of $(X \oplus C) + A$, and F_i is the carry at i th position of $X + B$. From the definition of s_i we get $s_{i+1} = (x_i \oplus c_i)a_i \oplus (x_i \oplus c_i)s_i \oplus a_i s_i = (x_i \oplus c_i)a_i \oplus (x_i \oplus c_i \oplus a_i)s_i = (x_i \oplus c_i)a_i \oplus (x_i \oplus c_i \oplus a_i)(\tilde{k}_i \oplus F_i)$.

From the definition of F_i we get $F_{i+1} = x_i b_i \oplus x_i F_i \oplus b_i F_i$. This means that \tilde{k}_{i+1} can be computed from x_i, a_i, b_i, c_i, F_i , and \tilde{k}_i . Further, we apply the algorithm demonstrated in [14]. The only difference is that for each bit position we have only two unknowns x_i and F_i , whereas in [14] have three unknowns. Yet, this difference is not crucial, and the algorithm can be applied.

Our experimental results (Monte-Carlo with 2^{32} trials), show that the probability that a solution exists, when A, B, C and K are randomly chosen is around 2^{-12} . \square